The ABC Effect in Double-Pionic Nuclear Fusion and a pn Resonance as its Possible Origin

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Abstract

The ABC effect – a long-standing puzzle in double-pionic fusion – has been reexamined by the first exclusive and kinematically complete measurements of solid statistics for the fusion reactions $pn \to d\pi^0\pi^0$, $pd \to ^3\mathrm{He}\pi\pi$ and $dd \to ^4\mathrm{He}\pi\pi$ using the WASA detector, first at CELSIUS and recently at COSY — the latter with a statistics increased by another two orders of magnitude. In all cases we observe a huge low-mass enhancement in the $\pi\pi$-invariant mass accompanied by a pronounced $\Delta\Delta$ excitation. For the most basic fusion reaction, the $pn \to d\pi^0\pi^0$ reaction, we observe in addition a very pronounced resonance-like energy dependence in the total cross section with a maximum 90 MeV below the $\Delta\Delta$ mass and a width of only 50 MeV, which is five times smaller than expected from a conventional t-channel $\Delta\Delta$ excitation. This reveals the ABC effect to be the consequence of a s-channel resonance with the formfactor of this dibaryonic state being reflected in the low-mass enhancement of the $\pi\pi$-invariant mass. From the fusion reactions to ^{3}He and ^{4}He we learn that this resonance is robust enough to survive even in nuclei.

Key words: $\Delta\Delta$ excitation, ABC effect
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The two-pion production in nucleon-nucleon collisions has been studied systematically at the storage rings CELSIUS and COSY. At energies near threshold the single-nucleon excitation is favored. Since single-Δ excitation is highly suppressed, single-Roper excitation dominates the near-threshold $\pi\pi$ production. At higher energies double-nucleon excitations come into play. For $T_p > 1$ GeV the $\Delta\Delta$ excitation becomes the leading process as observed in the respective $N\pi$ invariant mass spectra. Whereas this is in qualitative agreement with theoretical predictions, we find from the full information present in the data that the $\Delta\Delta$ system behaves very differently from what has been predicted.

In order to shed more light onto this problem, a long-standing puzzle in $\pi\pi$ production has been reexamined: the so-called ABC-effect. This acronym stands for an unexpected

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enhancement at low masses in the invariant $\pi\pi$ mass spectrum $M_{\pi\pi}$ first observed by **A**bashian, **B**ooth and **C**rowe in the double pionic fusion of deuterons and protons to ^{3}He [1]. Follow-up experiments [2] revealed this effect to be of isoscalar nature and to show up in cases where the two-pion production process leads to a bound nuclear system. With the exception of low-statistics bubble-chamber measurements all experiments conducted on this issue have been inclusive measurements carried out preferentially with single-arm magnetic spectrographs for the detection of the fused nuclei.

Initially the low-mass enhancement had been interpreted as an unusually large $\pi\pi$ scattering length and evidence for the σ meson [1], respectively. Since the effect showed up particularily clear at beam energies corresponding to the excitation of two Δs in the nuclear system, the ABC effect was interpreted later on by a t-channel $\Delta\Delta$ excitation in the course of the reaction process leading to both a low-mass and a high-mass enhancement in isoscalar $M_{\pi\pi}$ spectra [3,4,5,6,7,8].

With the WASA 4π detector[9] first at CELSIUS and more recently in the COSY ring we have measured the double-pionic fusion processes to D, ^{3}He and ^{4}He exclusively and kinematically complete with a statistics which is orders of magnitude higher than in previous measurements. For the most basic fusion process, the one leading to deuterium, first preliminary results from the data analysis are now available, see Fig. 1, which are in full support but of much higher quality than those taken at CELSIUS [10]: On top the spectrum of the $\pi^0\pi^0$-invariant mass $M_{\pi^0\pi^0}$ is shown in dependence of total energy in the center-of-mass system. Our data exhibit an enormeous low-mass enhancement, however, no apparent high-mass enhancement as predicted by conventional $\Delta\Delta$ calculations. Moreover the $\sqrt{s}$ dependence in the total cross section (bottom) reveals an unexpected and narrow resonance-like structure — again in contradiction to the conventional $\Delta\Delta$ process (dotted curve for the $\pi^0\pi^0$ channel). As we see, the ABC-effect, i.e. the low-mass enhancement is correlated to this narrow resonance structure, which has its maximum 90 MeV below the $\Delta\Delta$ mass and a width of only 50 MeV, *i.e.* five times smaller than expected from the conventional t-channel $\Delta\Delta$ excitation. Indeed, describing this structure by a s-channel *ansatz* leads to a surprisingly good description of both the total and the differential distributions including the ABC effect in the $M_{\pi^0\pi^0}$ spectra. The quantum numbers of this resonance have to be $I(J^P) = 0(1^+, 3^+)$. Such a resonance has been predicted by various theoretical calculations [11,12,13,14,15,16], some of which even predict this resonance to be a member of a dibaryon multiplet [17].

From the fact that the ABC effect is observed also for double-pionic fusion processes to heavier nuclei, we conclude that this resonance is robust enough to survive in nuclei.

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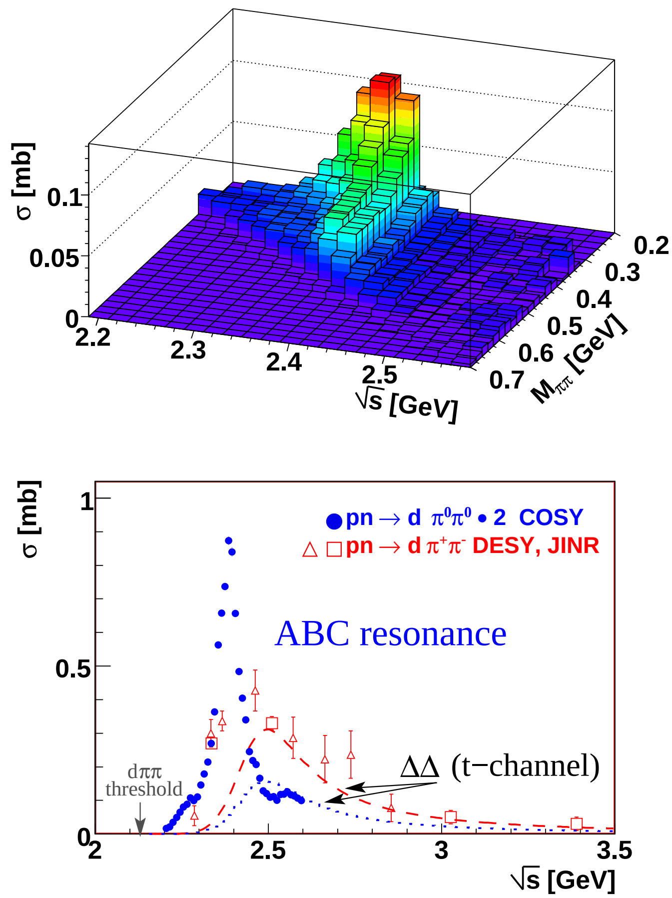

Fig. 1. Top: Energy dependence of the $\pi^0\pi^0$ invariant mass $M_{\pi^0\pi^0}$ depicted by a 3D-plot of $M_{\pi^0\pi^0}$ versus the total energy in the center-of-mass system $\sqrt{s}$. Bottom: Energy dependence of the total cross section for the $pn \to d\pi^+\pi^-$ reaction from threshold up to $\sqrt{s} = 3.5$ GeV. Data for the $d\pi^+\pi^-$ channel are from JINR Dubna (squares) and DESY (open triangles). The preliminary results of this work for the $\pi^0\pi^0$ channel — scaled by the isospin factor of two — are given by the full circles. Dashed and dotted lines represent t-channel $\Delta\Delta$ calculations for $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, respectively.

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